

# Recent LHCb Results

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**Abstract.** The LHCb experiment started its physics program with the  $37 \text{ pb}^{-1}$  of pp collisions at  $\sqrt{s}=7 \text{ TeV}$  delivered by the LHC during 2010. The performances and capability of the experiment, conceived for precision measurements in the heavy flavour sector, are illustrated through the first results from the experimental core program. A rich set of production studies provide precision QCD and EW tests in the unique high rapidity region covered by LHCb. Notably, results for W and Z production are very encouraging for setting constraints on the parton PDFs.

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## THE CONCEPT OF LHCb

The LHCb experiment[1] is searching for new physics through non standard virtual contributions to CP violating and rare decays of heavy hadrons. It is implemented as a single arm spectrometer covering the pseudorapidity region  $1.9 < \eta < 4.9$ , where the largest production rate of  $b\bar{b}$  pairs per solid angle is expected at LHC energies. This coverage is unique at the LHC and complementary to the general purpose detectors ATLAS and CMS. The detector design, sketched in fig. 1, emphasizes proper time

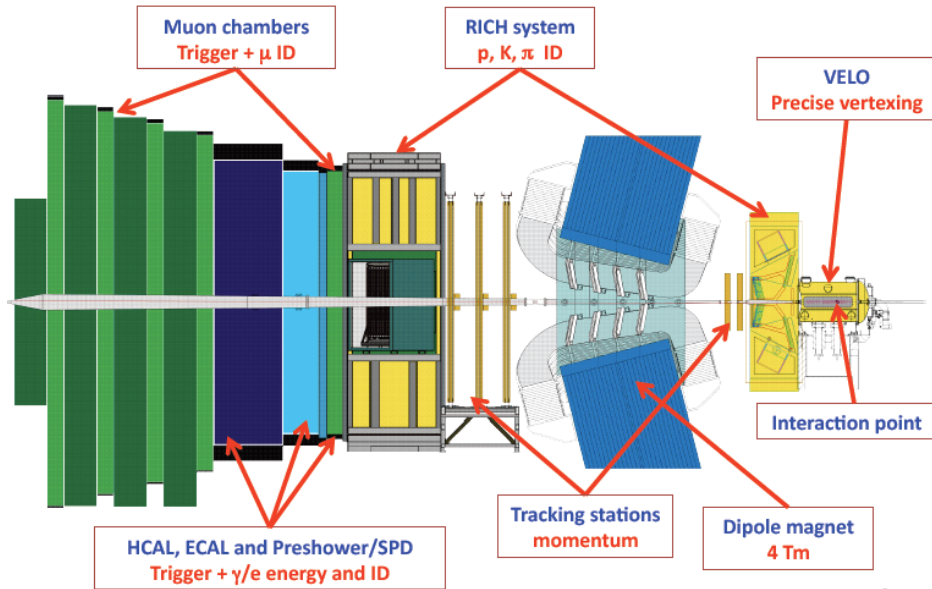


FIGURE 1. The LHCb detector

resolution, to identify the short lived  $b$  hadrons and resolve the fast  $B_s^0$  oscillations, while excellent invariant mass resolution and particle identification (PID) capabilities are needed to disentangle decays of heavy flavours from the dominant hadronic background. These detector features also make LHCb a powerful tool for heavy flavour spectroscopy and production studies in its unique rapidity range, providing precision QCD tests at the unprecedented energies reached by the LHC.

The geometry of the Vertex Locator (VELO) is optimized for detecting the decays of  $b$  hadrons in the forward direction. Its Si  $\mu$ -strips sensors are perpendicular to the beam and are located on two retractable half stations. When stable beam is declared, the two halves are closed and the inner border of the active area is only 8 mm away from the beam axis. Tracking is completed by a set of stations equipped with Si  $\mu$ -strips (for the inner part) and straw tubes (for the outer part), located upstream and downstream a warm dipole magnet providing an integrated field of 4 Tm. The combined performances of two RICH detectors result in excellent  $\pi/K/p$  separation in the 1–100 GeV/c momentum range. The calorimetric system provides  $e/\gamma$ /hadrons separation through a scintillating pad detector, a preshower, electromagnetic (shashlik) and hadronic (Fe/scint. tiles) calorimeters. Muons are identified by five stations equipped with multi-wire proportional chambers (or GEM chambers for the most inner part), interspaced by iron absorbers. A fast, flexible and efficient trigger is essential to extract the interesting events from the nominal 40 MHz collision rate. It is implemented in two levels: the initial decision comes from an hardware level (L0), selecting particles of high transverse momentum using the informations from the calorimetric and muon systems, which can operate at 40 MHz with a relatively low  $p_T$  threshold ( $\sim 1$  GeV/c). A software level (HLT), running on a massive computer farm, performs an online event reconstruction, reducing the event rate from 1 MHz to 2–3 kHz through inclusive and exclusive selections.

The experiment was designed to work at a luminosity of  $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ , 50 times lower than the LHC design luminosity, in order to minimize the pile-up.

## THE 2010 RUN

During its spectacular startup in 2010, the LHC machine gradually increased luminosity over 5 orders of magnitude, reaching the nominal LHCb value already by the end of the run. Due to the limited number of colliding bunches in this phase, LHCb acquired events with up to 2.6 visible collisions per crossing, six times the design value. The flexibility of trigger and DAQ systems allowed the experiment to cope with this high pile-up while keeping high efficiency for key channels, thereby maintaining the statistics for physics studies. The detector was fully working, with a negligible amount of dead channels in all subsystems, and the overall DAQ efficiency was 90%. Eventually, LHCb recorded an integrated luminosity of  $37 \text{ pb}^{-1}$ , similar to ATLAS and CMS. Though being a small sample compared to the nominal  $2 \text{ fb}^{-1}$  per year expected in the longer term, this dataset corresponds already to about 5 billion  $b$  events in the detector acceptance, sufficient statistic for the first competitive physics results, as well as the validation of detector performances. We will present in this contribution a selection of results from  $b$  decays, illustrating the potentiality of the experiment, followed by an overview of QCD and EW studies at LHCb.

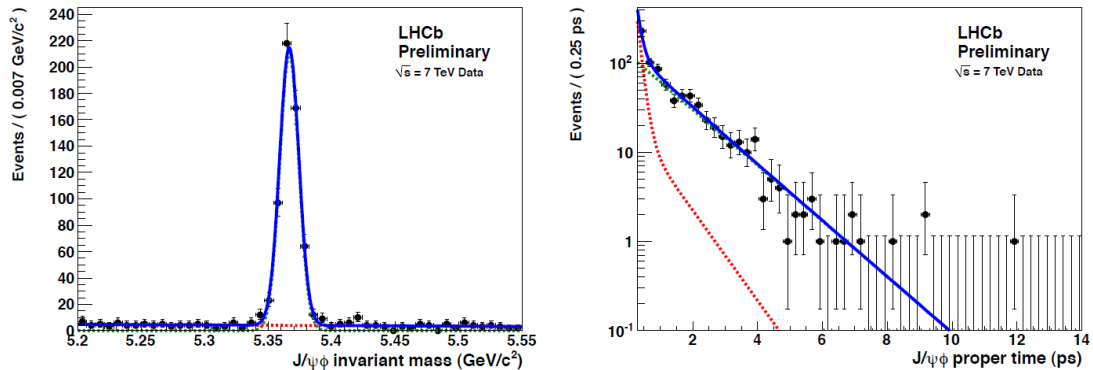
## PROPER TIME RECONSTRUCTION AND THE $B_s^0$

The VELO vertex resolution was measured on real data by comparing the reconstructed vertexes from randomly chosen subgroups of tracks in the same primary vertex. For a typical vertex of 25 tracks, a resolution of 16 (76)  $\mu\text{m}$  was obtained for the transverse (longitudinal) direction. The impact parameter resolution was measured to be  $13 + (26 \text{ GeV}/c)/p_T$   $\mu\text{m}$ , corresponding to a typical proper time resolution for  $B$  decays of 50 fs. Preliminary results([2], LHCb-CONF-2011-001) for the lifetime measurements of  $B^0, B^+, B_s^0$  and  $\Lambda_b$ , using final states containing a  $J/\psi$ , are shown on table 1. The excellent agreement with PDG averages demonstrates the level of control on the lifetime scale.

**TABLE 1.** Event yields and lifetimes obtained from several  $b$  hadron decays to exclusive states containing a  $J/\psi$  in the range  $0.3 < t < 14$  ps. Events are triggered using dimuon candidates with invariant mass compatible with the  $J/\psi$  and minimum  $p_T$  of 500 MeV/c, without any bias on lifetime. The current PDG values for the lifetimes are shown for comparison.

Channel	event yield	lifetime (ps), with stat. and syst. error	PDG2010 (ps)
$B^+ \rightarrow J/\psi K^+$	$6741 \pm 85$	$1.689 \pm 0.022 \pm 0.047$	$1.638 \pm 0.011$
$B^0 \rightarrow J/\psi K^{*0}$	$2668 \pm 58$	$1.512 \pm 0.032 \pm 0.042$	$1.525 \pm 0.009$
$B^0 \rightarrow J/\psi K_S$	$838 \pm 31$	$1.558 \pm 0.056 \pm 0.022$	$1.525 \pm 0.009$
$B_s^0 \rightarrow J/\psi \phi$	$570 \pm 24$	$1.447 \pm 0.064 \pm 0.056$	$1.477 \pm 0.046$
$\Lambda_b \rightarrow J/\psi \Lambda$	$187 \pm 16$	$1.353 \pm 0.108 \pm 0.035$	$1.391^{+0.038}_{-0.037}$

$B_s^0$  mesons, largely unexplored at the B factories, provide some of the most promising channels for the emergence of new physics. From the “golden mode”  $B_s^0 \rightarrow J/\psi \phi$  the CP-violating oscillation phase  $\phi_s$ , for which an accurate (error  $\sim 2$  mrad) SM prediction exists, can be measured. Figure 2 shows the invariant mass and lifetime distributions for the candidate events from lifetime unbiased triggers. The combination of impact parameter, invariant mass resolution (7 MeV/c<sup>2</sup>, with the  $J/\psi$  mass constrained to the PDG value) and PID performances results in a very clean event sample. As can be seen



**FIGURE 2.** Invariant mass (left) and proper time  $t$  (right) distributions for the  $B_s^0 \rightarrow J/\psi \phi$  candidates with  $t > 0.3$  ps. The signal (green dashed line), background (red dashed line) and total (blue solid line) contributions obtained from a two-dimensional fit are shown on the plots.

from table 1, despite the limited statistics, the accuracy of the lifetime measurement in this mode is already comparable with the Tevatron results, obtained from  $\sim 100$  times more integrated luminosity.

Flavour oscillations of  $B_s^0$  mesons were searched for in the more abundant  $D_s\pi$  and  $D_s3\pi$  modes. Neural network based tagging algorithm were developed and calibrated on real data using self-tagging modes. The limited statistics of the control modes is presently the main source of uncertainty and prevents the use of the powerful same side tagger for  $B_s^0$  with this dataset. However, a tagging power of  $3.8 \pm 2.1\%$  was obtained, allowing  $B_s^0$  oscillations to be observed, with a frequency measured to be ([2], LHCb-CONF-2011-005):

$$\Delta m_s = 17.63 \pm 0.11(\text{stat}) \pm 0.04(\text{syst}) \text{ ps}^{-1}$$

as illustrated in figure 3. The measurement agrees well with the world's best published result to date from CDF ( $17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1}$ ).

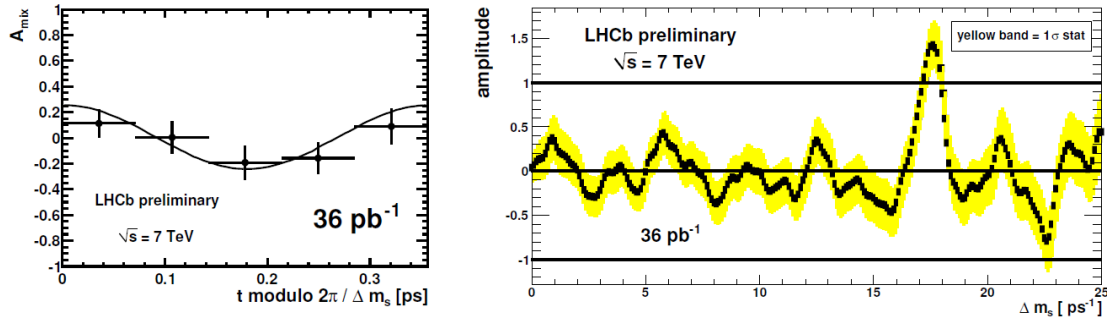
A time-dependent tagged analysis was performed for  $B_s^0 \rightarrow J/\psi \phi$ , leading to a first loose bound on  $\phi_s$  ([2], LHCb-CONF-2011-006). We expect to reach an accuracy of 35 mrad, comparable to the SM predicted value, with the first inverse fb of data expected in 2011.

Another key  $B_s^0$  channel is the ultra-rare  $\mu^+\mu^-$  decay, with a predicted BR of  $(3.2 \pm 0.2) \cdot 10^{-9}$  in the SM, that could receive significant contributions from new pseudo-scalar intermediate states. The channel is also very clean experimentally, with no significant peaking background. The analysis of the full  $37 \text{ pb}^{-1}$  data sample showed no candidate events, leading to a 95% CL limit of [3]

$$BR(B_s^0 \rightarrow \mu^+\mu^-) < 5.6 \cdot 10^{-8}$$

which is very close to the best limit from CDF ( $4.3 \cdot 10^{-8}$ ), obtained from  $3.7 \text{ fb}^{-1}$ . The sensitivity is expected to attain the SM level in LHCb with about  $2 \text{ fb}^{-1}$ .

The competitiveness of the experiment for  $B_s^0$  physics is also demonstrated by the first observation of several decay channels:  $B_s^0 \rightarrow D_{s2}X\mu\nu$ ,  $B_s^0 \rightarrow K^{*0}K^{*0}$ ,  $B_s^0 \rightarrow D^0K^*$ ,  $B_s^0 \rightarrow J/\psi f_0$  [4, 5, 2]. The latter, a CP eigenstate, can provide an interesting contribution to the measurement of  $\phi_s$ .



**FIGURE 3.** Preliminary results of the  $B_s^0$  oscillations analysis. On the left: the flavour asymmetry for  $B_s^0$  candidates as a function of proper time modulo  $2\pi/\Delta m_s$ . The fitted asymmetry is superimposed. On the right: fitted oscillation amplitude as a function of  $\Delta m_s$ .

## PARTICLE ID AT WORK

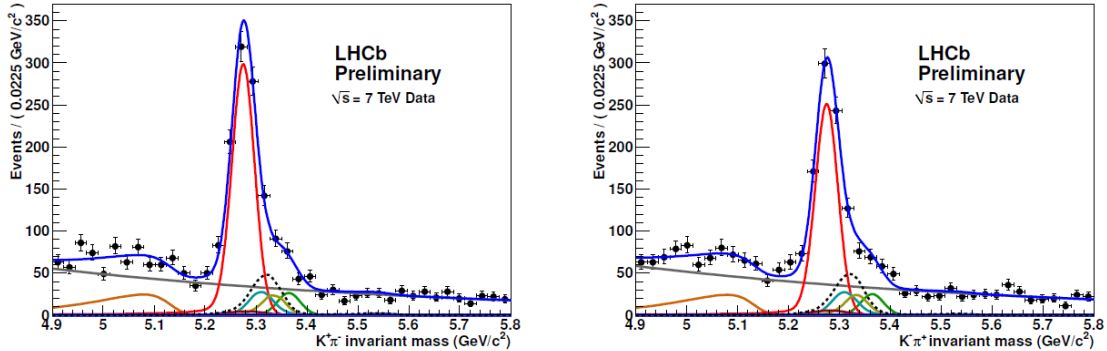
The most spectacular demonstration of the RICH's performances is provided by the analysis of charmless  $B \rightarrow hh$  decays, where  $\pi/K/p$  discrimination is essential to disentangle the  $B^0 \rightarrow \pi^+\pi^-$ ,  $B^0 \rightarrow K^+\pi^-$ ,  $B_s^0 \rightarrow K^+K^-$ ,  $B_s^0 \rightarrow \pi^+K^-$ ,  $\Lambda_b \rightarrow pK^-$  and  $\Lambda_b \rightarrow p\pi^-$  modes. PID performances are calibrated on real data using the abundant  $D^*$  and  $\Lambda$  decays. The  $B \rightarrow hh$  yields are then fitted simultaneously taking into account the expected cross feeds. The  $B^0 \rightarrow \pi^+\pi^-$  and  $B_s^0 \rightarrow K^+K^-$  modes will allow for a measurement of the CKM angle  $\gamma$  from loop diagrams. From the 2010 data sample we extract promising yields of  $275 \pm 24$   $B^0 \rightarrow \pi^+\pi^-$  and  $333 \pm 21$   $B_s^0 \rightarrow K^+K^-$  candidates, corresponding to about one fourth of what obtained by CDF from  $1 \text{ fb}^{-1}$ .

Although more statistics is needed for a competitive  $\gamma$  measurement, with 2010 data we already reached the sensitivity to confirm the direct CP violation in the  $B^0 \rightarrow K^+\pi^-$  mode from the time integrated CP asymmetry, as shown in figure 4. The possible biases on the measured raw asymmetry were constrained from real data: the detector asymmetry was found to be  $A_D = -0.004 \pm 0.004$  from  $D, D^* \rightarrow K\pi$  decays, while the production asymmetry was estimated to be  $A_p = 0.009 \pm 0.008$  from  $B^\pm \rightarrow J/\psi K^\pm$ . The results, compared with world averages from HFAG, are ([2], LHCb-CONF-2011-023):

mode	LHCb (preliminary)	HFAG average
$A_{CP}(B^0 \rightarrow K^+\pi^-)$	$-0.077 \pm 0.033 \pm 0.007$	$-0.098^{+0.012}_{-0.011}$
$A_{CP}(B_s^0 \rightarrow \pi^+K^-)$	$0.15 \pm 0.19 \pm 0.02$	$0.39 \pm 0.17$

The  $2.3\sigma$  effect for  $B^0$  is the first hint for CP violation measured at LHC. Also in this case, the measurement for  $B_s^0$  is already competitive with the world average.

Performances of the calorimeters were also excellent, with a resolution of  $7.2 \text{ MeV}/c^2$  for the  $\pi^0$  mass from unconverted photons and a response uniformity within 2%. Despite the harsh hadronic environment and the high pile-up experienced in 2010, clean samples of exclusive radiative decays as  $B^0 \rightarrow K^*\gamma$  and  $\chi_c \rightarrow J/\psi\gamma$  could be reconstructed, implying nice prospects for the physics with the rare  $b \rightarrow s\gamma$  modes.



**FIGURE 4.** Invariant mass distributions for (left)  $B^0 \rightarrow K^+\pi^-$  and (right)  $B^0 \rightarrow K^-\pi^+$  candidates. The dots represent the data, while the curves show the result of the unbinned ML analysis fit: total (blue), signal (red), combinatorial background (gray) and cross-feed components from the other  $B \rightarrow hh$  modes.

## LHCb AS A GENERAL PURPOSE FORWARD DETECTOR

Particle production rates can be studied by LHCb in a rapidity range complementary to the general purpose detectors. The excellent PID and vertexing capabilities, combined with the low  $p_T$  thresholds of the trigger, allow to select a wide range of exclusive states with good efficiency. LHCb can contribute in particular to heavy flavour spectroscopy, studying of  $X(3872)$  and the other unexpected states recently observed, the  $B_c$  and the other double heavy flavour states. We summarize here some of these studies, that are discussed in more details in the other LHCb contributions to these Proceedings.

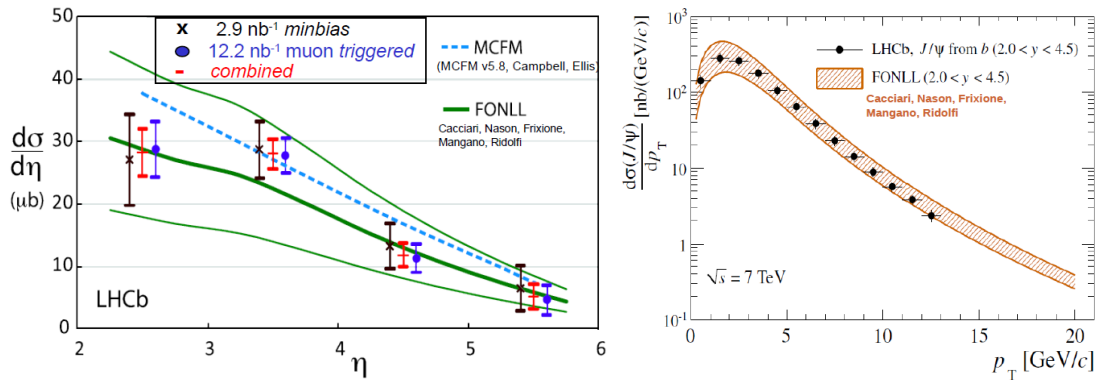
The production cross section of  $b$  hadrons is of obvious importance for LHCb, but also as a QCD testbench and as a crucial input for background determination in many key channels at LHC, notably the search for the Higgs boson. It was measured using the inclusive  $b \rightarrow D^0 X \mu^- \nu$  mode from just the first  $15 \text{ nb}^{-1}$  of data [6]. A measurement of similar accuracy was possible with  $5 \text{ pb}^{-1}$  using events with a delayed  $J/\psi$  decaying to  $\mu^+ \mu^-$  [7]. The results, compared to some theoretical predictions, are showed in fig. 5. Extrapolating to the full rapidity range, we get

$$\begin{aligned} \sigma(p\bar{p} \rightarrow b\bar{b}X)|_{s=7 \text{ TeV}} &= (284 \pm 20 \pm 49) \mu b & (b \rightarrow D^0 X \mu^- \nu) \\ &= (288 \pm 4 \pm 48) \mu b & (b \rightarrow J/\psi X), \end{aligned}$$

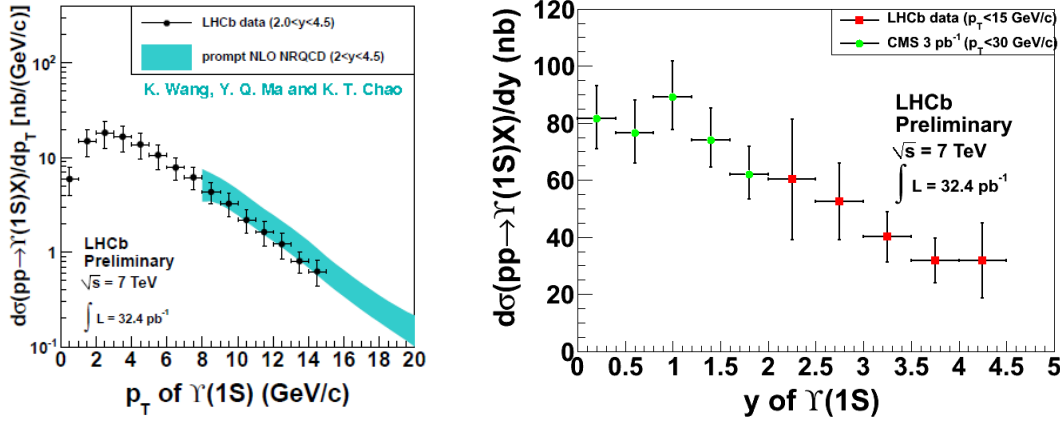
in good agreement with the production models tuned on the Tevatron results.

The first low-luminosity data allowed LHCb to allocate a relevant fraction of the trigger bandwidth to charm physics. Production of all open charm states was measured using minimum-bias trigger, resulting in valuable QCD tests (notably from the  $D^+/D_s^+$  production ratio) and reducing uncertainties for backgrounds in many CPV measurements.

A rich quarkonium physics program has begun by measuring the production rates of prompt  $J/\psi$ ,  $\psi(2S)$ ,  $\chi_c$ ,  $\Upsilon(1S)$ . Figure 6 shows the results for bottomonium, compared with the CMS values at lower  $\eta$ , nicely illustrating the complementarity of LHC experiments. Data also cover production at very low transverse momentum, down to less than  $1 \text{ GeV}/c$ , well below the typical threshold of theoretical predictions!



**FIGURE 5.** Results of  $b\bar{b}$  cross section measurements from charm events (left, as a function of pseudorapidity) and from delayed  $J/\psi$  (right, as a function of the  $J/\psi$  transverse momentum), compared to theoretical predictions.



**FIGURE 6.** The cross section for  $\Upsilon(1S)$  production is shown as a function of transverse momentum (left, compared with theory) and pseudorapidity (right, compared to CMS in the central region).

Double  $J/\psi$  production was also observed, as well as  $B_c$  production in the  $J/\psi \pi^+$  channel ([2], LHCb-CONF-2011-009 and LHCb-CONF-2011-017), paving the way for the exploration of states from double heavy flavour production.

## SCRUTINIZING PARTON PDFS

The LHCb rapidity region allows the study of deep inelastic scattering in the unique unexplored high- $Q^2$  regions at very low  $x$ . Drell-Yan production of muon pairs can be observed for  $Q^2 > 5 \text{ GeV}^2$ , probing parton PDFs down to  $x \sim 10^{-6}$ . Production of  $W$  and  $Z$  bosons, corresponding to  $x \sim 10^{-4}$ ,  $Q^2 = M_{W,Z}^2$ , has been observed already with the first  $17 \text{ pb}^{-1}$  of data ([2], LHCb-CONF-2011-012).

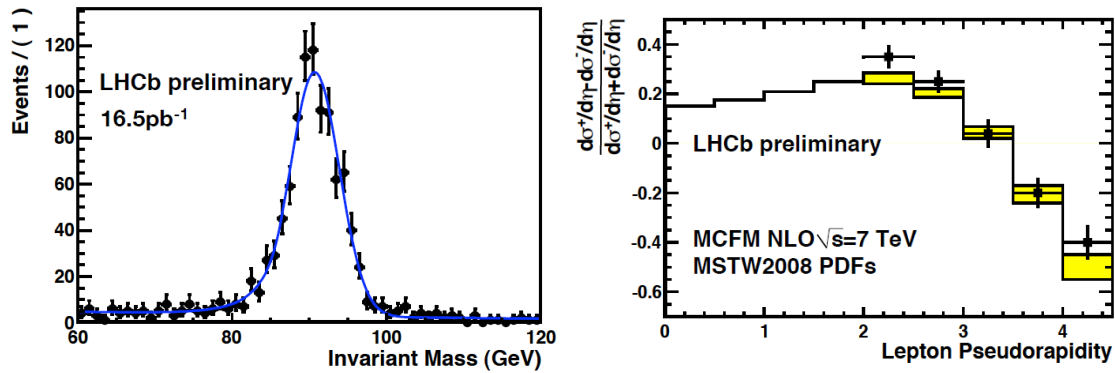
The cross sections are predicted with accuracy varying with  $\eta$  from 3 to 10%, the uncertainty on parton PDFs contributing to a large extent. Constraints to the PDFs can thus be obtained, particularly from the charge asymmetry of  $W$  production, since many systematics cancel and its  $\eta$  dependence is very sensitive on PDFs.

A clean sample of  $Z \rightarrow \mu^+ \mu^-$  decays can be easily selected using the invariant mass constraint on muons having  $p_T > 20 \text{ GeV}/c$ , with almost no background expected. With an estimated 69% efficiency, 833 candidate events survive the selection (see fig. 7).

The signature for  $W$  decays is momentum imbalance in the transverse plane, with an isolated high- $p_T$  ( $> 20 \text{ GeV}/c$ ) muon and little other activity in the event to suppress background from QCD jets. The muon is also required to be compatible with the primary vertex to suppress backgrounds from  $b, c$  decays. For the resulting 7624  $W^+$  and 5732  $W^-$  candidates we estimate a selection efficiency of 30% and a signal to background ratio of about 1.6. The resulting cross sections are

$$\begin{aligned}
 \sigma_Z(81 < m_Z < 101 \text{ GeV}/c^2) \times BR(Z \rightarrow \mu^+ \mu^-, 2 < \eta_\mu < 4.5, p_{T\mu} > 20 \text{ GeV}/c) &= 73 \pm 4 \pm 7 \text{ pb} \\
 \sigma_{W^+} \times BR(W \rightarrow \mu \nu, 2 < \eta_\mu < 4.5, p_{T\mu} > 20 \text{ GeV}/c) &= 1007 \pm 48 \pm 100 \text{ pb} \\
 \sigma_{W^-} \times BR(W \rightarrow \mu \nu, 2 < \eta_\mu < 4.5, p_{T\mu} > 20 \text{ GeV}/c) &= 682 \pm 40 \pm 68 \text{ pb}
 \end{aligned}$$





**FIGURE 7.** On the left, invariant mass distribution for the  $Z \rightarrow \mu^+ \mu^-$  candidates. On the right, charge asymmetry of the  $W$  production as a function of  $\eta_\mu$ , compared with the prediction of the NLO MCFM generator. The shaded area shows the uncertainty due to the MSTW08 PDF set used in the model.

The systematic errors are dominated by the uncertainty on luminosity, a component which cancels in the ratios. As shown in fig. 7, the error on the  $W$  charge asymmetry is already comparable to the uncertainty due to the PDFs. With the much larger statistics expected for 2011, LHCb will start contributing to the determination of the proton structure.

## CONCLUSIONS

The first data sample acquired in 2010 provided a proof of principle of the LHCb concept. With only 37 pb<sup>-1</sup>, all the necessary ingredients for the key  $B$  physics measurements, namely proper time resolution, background suppression and tagging capabilities, have been demonstrated. The first world class results show that LHCb is already picking up the baton from the successful Tevatron  $B$  physics program, confirming how high-precision measurements in the heavy flavour sector can be achieved at hadron colliders.

LHCb physics is also expanding well beyond the core program, with many original results on production studies in the unique forward region covered by the experiment, as documented by the other 8 LHCb contributions to this conference.

According to the LHC schedule, we expect to collect our first fb<sup>-1</sup> within the 2011 run. A wide range of unexplored flavour territories is opening out in front of us.

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